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Probabilistic basis development of standardization of snow loads on building structures

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Ensuring the reliability and safety of buildings and structures largely depends on a proper understanding of nature and quantitative description and rationing of loads on building structures, including snow loads. Analysis of the evolution of domestic snow load codes together with their statistical substantiation is an urgent task. The article contains a systematic review of codes and publications on the problem of snow load over the 80-year period from the 40s of the twentieth century to the present. The main attention is paid to the tendencies analysis of designing codes development concerning changes of territorial zoning and design coefficients, the appointment of normative and design values of snow load, and involvement in it of experimental statistical data. There is a high scientific level of domestic code DBN B.1.2-2006 "Loads and effects", which have a modern probabilistic basis and are associated with the codes of Eurocode. Scientific results that can be included in subsequent editions of snow load standards are highlighted.

Keywords: snow observations, snow load, territorial zoning, normative load, design load

Розвиток імовірнісних засад нормування снігового навантаження на будівельні конструкції

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Забезпечення надійності та безаварійності будівель і споруд у великій мірі залежить від правильного розуміння природи і кількісного опису та нормування навантажень на будівельні конструкції, в тому числі снігових навантажень. Ці навантаження на споруди мають досить складну фізичну природу і мінливий характер, що вимагають знання термодинамічних процесів в атмосфері і на ґрунті, фізичних властивостей снігу, методики метеорологічних спостережень і кліматологічного опису місцевості, мінливості навантажень, характеру відкладення снігу на конструкціях і спорудах. Такі особливості у певній мірі відображаються в розділах норм проектування будівельних конструкцій, що містять нормативи снігового навантаження. Більшість параметрів норм снігового навантаження мають імовірнісну природу і вимагають для свого обґрунтування застосування статистичних методів. Ці методи постійно змінювалися і розвивалися разом з регулярним переглядом норм будівельного проектування. Аналіз еволюції вітчизняних норм снігового навантаження разом з їх статистичними обґрунтуванням є актуальною задачею. Матеріали, присвячені сніговим навантаженням, опубліковані в різних науково-технічних журналах, збірниках статей, матеріалах конференцій. Стаття містить систематизований огляд норм проектування та публікацій по проблемі снігового навантаження за 80-річний період з 40-х років XX століття до теперішнього часу. Головна увага приділяється аналізу тенденцій розвитку норм проектування конструкцій в частині змін територіального районування та розрахункових коефіцієнтів, призначення нормативних і розрахункових значень снігового навантаження і залучення до цього дослідних статистичних даних. Відзначається високий науковий рівень вітчизняних норм ДБН В.1.2-2006 «Навантаження і впливи», які мають сучасний імовірнісний базис і асоціюються з нормами Єврокод. Виділяються наукові результати, що можуть бути включеними в наступні норми снігового навантаження.

Ключові слова: снігові спостереження, снігове навантаження, територіальне районування, нормативне навантаження, розрахункове навантаження

Introduction

Ensuring the reliability and trouble-free operation of buildings and structures depends on a correct understanding of the nature, quantitative description, and regulation of loads on building structures, including snow loads. These loads on structures are of a rather complex physical nature and changeable character, requiring knowledge of thermodynamic processes in the atmosphere and on the ground, physical properties of snow, methods of meteorological observations and climatological description of the terrain, variability of loads, the nature of snow deposition on buildings and structures. These features are reflected to a certain extent in the sections of the codes for the building structures design containing the standards for the snow load. Most of the parameters of the snow load codes are of a probabilistic nature and require the use of statistical methods for their substantiation. These methods have been constantly changing and evolving together with the regular revision of building design codes. Analysis of the evolution of domestic snow load norms, together with their statistical justification, is an urgent problem.

Review of research sources and publications

Regular snow measurements have been carried out since the end of the 19th century. In the 1930s, their results served as the basis for the compilation of the first normative document on snow load and the first publications on this problem [1]. This process has intensified with the preparation for the transition of structural calculations to the method of limit states [2, 3]. In subsequent years, along with the regular revision of the codes of loads and effects on structures, the regulation of the snow load was improved. The evolution of snow codes was covered in publications of leading scientific and technical journals [4–14]. Reviews of the development of snow codes have been published as sections of monographs and dissertations devoted to loads on buildings and structures [18–21]. Since the 90s of the last century, design standards have been developed by separate states that were previously part of the USSR. In this regard, probabilistic studies of the snow load on the territory of Ukraine became more active [25–30], the result of which was the corresponding section DBN V.1.2-2006 "Loads and effects". In subsequent years, studies of the snow load continued along with the substantiation and refinement of a number of code coefficients [31–35].

Definition of unsolved aspects of the problem

Materials on snow loads have been published in various scientific and technical journals, collections of articles, and conference proceedings. Access to these publications is difficult; some institutions began to destroy paper magazines of the past years, motivating the transition to electronic editions. However, in reality, the transfer to electronic form has occurred so far only for publications published after 2000. Published reviews of the snow load regulation development are incomplete and do not include the results of studies of the last 15 – 20 years.

Problem statement

The article contains a systematized review of publications in leading scientific and technical journals on the problem of snow load for the period from the 40s of the twentieth century to the present. The main attention is paid to the analysis of the evolution of structural design codes in terms of changes in territorial zoning and design coefficients, the appointment of normative and design values of the snow load, and the involvement of experimental statistical data. It highlights the scientific results that can be included in subsequent editions of snow load codes.

Basic material and results

The regulation of snow loads in the USSR was developed based on experience in the operation of buildings and structures, as well as with the improvement of methods for building structures calculating.

One of the first normative documents on the snow load in the USSR was the "Unified Norms" OST / VKS 7626 / B (introduced from June 1, 1933). A certain scientific basis for substantiating the codes at that time already existed: long-term meteorological snow observations; snowdrift research carried out since pre-revolutionary times at the St. Petersburg Institute of Railways and Moscow State University (laboratory of hydrodynamics, N.E. Zhukovsky); the results of snow accumulation studying on the roofs of industrial buildings, obtained by TsNIPS in the early 30s [1]. However, due to the limited source material, it can be assumed that the first domestic snow codes were drawn up based on expert assessments of specialists and taking into account the experience of operating buildings and structures. In this document, the snow load was normalized depending on the height of the snow cover h, and the average maximum height for the last ten years was taken into account. Thus, the design of snow depth had some statistical justification. At the same time, the density of snow, without sufficient explanation, was taken equal to ρ = 100 kgf/m^3. The design value of the snow load was determined as $p = 1{,}6\ \rho h$. On the territory of the Soviet Union, only 4 regions were identified with different snow cover heights and the corresponding snow load, determined from a map or table: the 1st region without permanent snow cover, for which the load was taken p = 25 kgf/m^2; 2nd region with a snow cover height h <30 cm and p = 40 kgf/m^2; 3rd area with a height of 30 cm $\le h \le$ 60 cm and p = 80 kgf/m^2; 4th region with h > 80 cm and p = 120 kgf/m^2. For mountainous areas, the height of the snow cover was presented in tabular form.

These codes determined such features of the snow load distribution on the roofs as the dependence on the roof slope and the presence of lanterns. It is interesting to note that for roofs with a slope of 20 ... 30° the snow load increased by 25% (in the subsequent versions of the codes, this increase is absent). For roofs with height discontinuity, a scheme was recommended with a 50% decrease in the snow load on elevated areas (but not less than 25 kgf/m^2) with an additional 50% load drift to the lower areas. Possible accumulation of snow (snow bag) with a maximum height equal to the height of the obstacle, but not more than *4h* was taken into account near-vertical obstacles. A triangular shape of snow bags was assumed, but the codes did not contain recommendations for their length. The load from the snow bag was taken into account at the above-mentioned snow density $\rho = 100$ kg/m^3. For gable and vaulted roofs, the level of snow load was determined according to two options: full uniform loading of the entire span and one-sided loading of the half span.

In the determination of the snow load on the roof, the type of terrain was taken into account. For open areas with frequent strong winds at a speed of 12 m/s and more, the snow load was allowed to be reduced by 50%, but not less than 25 kgf/m^2. For areas closed from the wind, the snow load increased by 25%. The codes contained detailed recommendations for accounting for snow melting on roofs, as a result of which a sufficiently large (up to 50 ... 75%) decrease in snow load was allowed depending on the thermal resistance of the roof, internal air temperature, and the amount of heat release. However, in subsequent regulations, these recommendations were omitted.

A serious drawback of these codes was the underestimation of the accepted snow density, although at that time there was already information about its significantly higher values. So, according to TsNIPS [1], the density of freshly fallen snow was 85 ... 190 kg/m^3 (on average 135 kg/m^3), the maximum density during the winter – 240 ... 250 kg/m^3. As a result, the design snow loads quite often turned out to be noticeably lower than the actual loads. In addition, the codes included the snow cover height, measured using constant slats, which did not make it possible to fully take into account the terrain peculiarities and the wind regime. Taken by TsNIPS in 1932–1933 measurements of snow accumulation on the roofs of industrial buildings revealed the complex nature of the snow bags, which significantly differed from the simplified recommendations of the first domestic codes. From the height of historical experience, it is possible to assess the conjunctural and political shade of the underestimated loads codes of the 30s (this applied not only to snow loads), aimed at all-round savings in the construction of a country that was experiencing massive industrialization. Despite this, such rationing provided a generally satisfactory operation of buildings and structures, since relatively high safety factors were taken in the methodology for calculating structures for permissible stresses, which was in force at that time.

This was followed by OST 90058-40 (1940), compiled on the research results basis of the building aerodynamics laboratory of the Central Scientific Research Institute of Industrial Construction (TsNIPS). When substantiating the snow load code, the snow density was increased with differentiation depending on the snow cover height. At a height of $h > 50$ cm, the density $\rho \approx 200$ kg/m^3 was taken, for $h \approx 30$ cm – $\rho \approx 230$ kg/m^3 and for $h < 20$ cm – $\rho \approx 250$ kg/m^3. The territory of the USSR was divided into 5 snow regions with the following values of the snow cover height and the estimated weight of snow p on the surface of the earth at a slightly higher level compared to the previous codes: I region – height up to 20 cm, weight $p = 50$ kgf/m^2; II region – height from 20 to 40 cm, $p = 70$ kgf/m^2; III region – height from 40 to 60 cm, $p = 100$ kgf/m^2; IV region – height from 60 to 90 cm, $p = 150$ kgf/m^2; V region – height more than 90 cm, $p = 200$ kgf/m^2. For mountainous areas, the design weight of the snow cover (kgf/m^2) was recommended to be determined as $p_c = 2h$ (but not less than 60 kgf/m^2), where h is the average 10-year snow cover height in cm, taken from the data of meteorological observations. In this document, the recommendations for taking into account the coverage profile were slightly changed towards simplification.

The development of methods for calculating building structures, especially for assessing the safety factor of structures, required to objectively identify the parameters of loads and strength of materials [2]. Therefore, the need has increased to use statistical methods to describe snow loads, which have a distinctly random nature. An example of a statistical analysis of the snow cover was the distribution curves of the snow height for the Moscow region, built for the period from 1898 to 1935. N.S. Streletsky was the first who had used this data to numerically assess the reliability of steel truss structures, designed according to the codes in force at that time [3].

Further refinement of the snow load with the justification of the design values based on field observations was carried out in the post-war 50s of the twentieth century. Materials of snow surveys on the roofs of industrial buildings and new data on the features of the drift and melting of snow were obtained, which confirmed the need to adjust this code. Taking into account the new data, in 1954, Codes and Rules SNiP II-B.1-54 "Loads and effects" were introduced, in which the values of the snow load were increased for certain regions, in particular, the snow-covered territory in the region of Perm was assigned to the V snow region, to the IV snow region – the region of Novosibirsk, the need for which was evidenced by the publications of specialists. These codes were consistent with the introduction of structural analysis using the limit state method. When switching to this method, the values of the calculated weight of the snow cover according to the previous norms p were taken as the normative loads, i.e. average values of annual maximums. The design snow loads, which began to be interpreted as the highest possible during the operation of the structure, began to be determined by multiplying by the overload factor. This coefficient, due to the lack of reliable data on the variability of annual maximums, was taken to be common for the entire territory, $n = 1{,}4$. Thus, the normative load p increased by 40%. This correction was justified by the fact that p was determined as the average of the maximum weights of snow for each year (and the weight was determined from the average density of snow). Consequently, the actual values of snow loads can exceed the normative load in about 50% of winters. The design snow load on the buildings' roofs was determined as $p_c = npc$, where c is the coefficient introduced for the first time, taken depending on the profile of the roof. In this document, the recommendations for taking into account the roof profile were slightly changed towards simplification, which included the range $c = 0 ... 1,0$ for simple single-slope and gable roofs, $c = 0,3 ... 1,0$ for vaulted roofs, $c = 0,4 … 1,6$ for roofs with skylights, with only the transverse profile of the building taken into account. In buildings with a height difference H (m), the maximum height of the snow bag was specified $p_c = 200 \text{ H} \leq 4q$ with the length of the additional triangular part $a = 2H$, with $5 \text{ m} \leq a \leq 10$ m.

Damages and collapses of roofs in several cities [4–6] showed that the codes of that time did not provide the necessary reliability of roof structures. Therefore, further clarification of snow loads was required, primarily in places of increased snow accumulation. Based on the generalization of the results of mass measurements of snow cover on 50 roofs of various profiles in different regions, carried out in 1958-1959 at TsNIISK [7], in the development of SNiP II-B.1-54, were developed and approved in 1959 SN 69-59 "Guidelines for the determination of snow loads on the roofs of buildings." In these instructions, individual calculation schemes of snow loads, placed in the SNiP, were clarified, and new schemes for the distribution of loads for the most common roof profiles (12 schemes in total) were given [8]. It is taken into account that snow accumulations on vaulted roofs strongly depend on the strength and frequency of winds; snow load on such surfaces is increased by 25%. The loads from snow bags at the lanterns of single-span and multi-span buildings are differentiated, the load at the ends of the lanterns is highlighted and the schemes of snow loads on the roofs of two- and multi-span buildings without lanterns are supplemented. Additional accounting of snow load on parts of the span has been regulated, taking into account possible wind blowing off snow or carrying out snow cleaning operations. At the same time, it is envisaged to reduce the snow load by 20% on surfaces with excessive heat release, as well as for flat and gentle surfaces with a wind speed of at least 4,0 m/s. It is interesting to note that Soviet works of this period in the field of studying snow loads were well known abroad, were translated into English, and taken into account when compiling snow codes for Canada.

Recommendations SN 69-59 were included in the next edition of SNiP II-A.11-62 “Loads and effects” with minor changes. In this edition, the snow zoning of the USSR was clarified – 5 regions of the previous SNiP 1954 with normative values of 50 – 200 kgf/m^2 were left and a 6th region was introduced for Kamchatka with 250 kgf/m^2. The code developers had used data from 4075 weather stations and posts. They also took into account more reliable maps of the average annual maximum weight of the snow cover on the earth, built based on data from 140 meteorological stations. At the stations simultaneously with the height of the snow cover, its weight was measured and the average density was determined. They used the results of route snow surveys accumulated over the past 15 ... 20 years, the accuracy of which is significantly higher than measurements on three permanently installed rails [9]. It should be noted that in the absence of snow survey data, it was nevertheless allowed that the weight of the snow cover was determined by the formula $p_0 = 220\ H$, where H is the height of the snow cover in meters, taken from the data of meteorological observations as the average of the maximum annual heights in a protected place for a long-term period (at least 10 years). SNiP II-A.11-62 specifies the effect of wind on the level of snow loads due to wind drift from the roofs. As in the previously developed "Guidelines", for individual roof profiles of buildings located in areas with an average wind speed of at least 4 m/s for the three coldest months, a reduction in snow load by 20% was provided.

During this period, some researchers continued to work on the clarification and regulation of snow bags on the roofs [10]. A technical and economic comparison of the methods of snow removal from the roofs was carried out [11].

The next revision of SNiP II-6-74 “Loads and effects” was adopted 12 years later and had an almost modern look, including a map of the zoning of the USSR territory by weight of snow cover. These codes took into account the results of further studies of the methodology for determining the weight of snow cover, the study of the drift and transfer of snow under the wind influence, and statistical substantiation of overloading snow loads coefficients on buildings and structures. As in the previous editions of the codes, the regional snow load standard was determined as the average annual maximum obtained over a 10-year period based on long-term snow measurements. In this version of the codes, classification of loads was developed, in which temporary long-term loads were highlighted. They are addressed to structural calculations, taking into account the effect of the loads' action duration on displacements, deformations, and cracking (for example, for reinforced concrete structures). For the snow load without statistical justification, the weight of the snow cover of the III-VI regions, reduced by 70 kgf/m^2, was taken as the long-term part.

According to Institute “TsNIIPromzdaniya» data for 112 cities, the actual snow loads (kgf/m^2) in the indicated period exceeded the design ones (shown in brackets): I region 100 (70); II region 132 (98); III region 179 (140); IV region 252 (210) [11]. Considering this situation, as well as the fact that during the period of validity of SNiP II-A.11-62 there were cases of light roof accidents due to overloading with snow, a differentiated increased coefficient of overload was introduced into SNiP II-6-74. It depended on the ratio of the dead load q (own weight of the roof, including the weight of the suspended stationary equipment) to the normative weight of the snow cover p_0. For relatively heavy roofs with $q/p_0 = 1$ or more, the overload factor assumed the previous value of $n = 1.4$, with the relative lightening of the roof, it increased: at $q/p_0 = 0.8 – n = 1.5$; at $q/p_0 = 0.6 – n = 1.55$; at $q/p_0 = 0.4$ and less – $n = 1.6$.

In support of this proposal, its author Driving A.Ya. [12] gave the following considerations. The deadweight of heavy roofs is several times higher than the normative snow load. So, in region III, the normative snow load was 100 kgf/m^2, and the roof weight was 4–5 times more. Light roofs, on the contrary, had their own weight less than the normative snow load (in region III, 30–50% of the snow weight). When zoning the territory according to snow loads, their values were taken into account, which is possible once every 10 years. In fact, over a longer period of the structure's existence, snow loads may exceed the normative value (which has been repeatedly observed in practice). This excess for heavy roofs is insignificant and is within the calculation accuracy and tolerances. At the same time, the tolerances and overload factors taken into account in the design of lightweight roofs turn out to be insufficient, and exceeding the normative snow loads becomes dangerous for them.

A significant advantage of these codes edition is a more accurate and specific accounting of snowdrifts by the wind. This was preceded by experimental studies conducted at TsNIISK by Otstavnov V.A. and Rosenberg L.S. [13]. As a result, for flat roofs, the snow load was determined for each year, taking into account the snowdrift:

$$S = (1.24 - 0.13\ v_m)\ S_3 - q\ \Pi_2\ \tau\ , \qquad (1)$$

where S_3 is the maximum weight of snow that fell during the winter;
v_m – wind speed during snowfall;
q – the average intensity of snowdrift per day during a blizzard without snowfalls (depends on the wind speed during blizzards);
Π_2 – repeatability of wind speeds over 6 m/s in the absence of snowfall;
τ – the duration of snowdrift during the period of no snowfall.

As can be seen from formula (1), the phenomenon of snowdrift has a clear probabilistic nature, depending on several random factors, which were taken into account by the developers of the codes. As a result, it was substantiated that the normative load on flat and gently sloping roofs without lanterns with slopes of up to 12% and curved roofs with a boom-to-span ratio f/l <0,05, designed in areas with an average wind speed for the three coldest months $v \geq 2$ m/s, it is allowed to reduce it by multiplying by a factor $k = 1.2 - 0.1v$. For roofs with slopes from 12 to 20% in areas with $v \geq 4$ m/s, the normative snow load may be reduced by 15%. For buildings with a width of up to 60 m or a height of more than 20 m, the coefficient k is additionally reduced by 10%. In addition, the coefficient c of the transition from the weight of the earth snow cover to the snow load on non-insulated roofs of workshops with excessive heat release has been clarified. With slopes of such roofs of more than 3% and ensuring proper water drainage, this coefficient can be reduced by 20%. In this version of the codes, the schemes of snow loads on the roofs with complex profiles and parapet parts are also clarified.

SNiP II-6-74, which was in operation for 11 years, quite accurately regulated snow loads. However, the peculiarities of snow accumulation on certain types of roofs remained unaccounted, which caused numerous requests from design organizations. In this regard, TsNIISK 1982 issued "Recommendations for determining the snow load for some types of roofs" (developed by L. S. Rosenberg) as an addition to this version of the codes. They provide recommendations for taking into account the accumulation of snow near the ridge of a gable roof, on pointed arches and sagging cylindrical roofs. However, the questions of the design organizations to the developers of the codes (TsNIISK) continued. One of the most frequent questions was the following: how were the schemes of uneven snow deposition built at differences in the height of the roofs? One of the authors of the load codes Bat A.A. gave the following answer to this question [14]. In the determination of coefficient c, a single initial condition was used – the total amount of unevenly deposited snow on the surface should be equal to the amount of uniformly deposited snow. Part of the snow is blown down from the upper roof; snow also falls on the lower roof with a different wind direction. Therefore, the coefficient c increases as the lengths from which snowdrifts and onto which snow is applied increases. In this case, the experimentally established fact was taken into account that unevenness is observed on the lower cover at a length approximately equal to twice the height of the drop. Therefore, the maximum unevenness will decrease as the drop increases, and the height of the drop is in the denominator. The coefficient c characterizing the unevenness is limited by two conditions: $c \leq 200\ h/p_0$ – the limitation physically reflects the complete filling of the drop with snow; $c \leq 4$ for buildings and $c \leq 6$ for awnings – inequality takes economic considerations into account.

In subsequent years, several organizations continued to study the factors influencing the snow load. In particular, field observations of snow bags on various types of shells were carried out in the Krasnoyarsk, Sverdlovsk, and Chelyabinsk [15]. A one-sided trapezoidal scheme of snow loading of pointed arches was proposed, which was taken into account in the next edition of the codes [16]. A study of snow loads on flat surfaces of industrial buildings with skylights was carried out [17].

An active study of the loads on building structures in the 70-80s of the last century contributed to the release in 1985 of SNiP 2.02.07-85 "Loads and effects". This version of the codes, like the previous one, regulated six values of the quantity S_0 = 50 – 250 kgf/m^2, which corresponded to the number of snow regions on the territory of the former USSR. At the same time, most of the territory belonged to the III and IV snow regions, the areas south of 49º or 50° north latitude corresponded to the I and II snow regions (including Ukraine), the V region was mainly distributed in the Urals, Western Siberia, and Kamchatka, and the VI snow region was found only on Sakhalin. Snow load in mountainous areas was not standardized; it should have been established according to meteorological data. The normative values S_0 were noticeably increased in the foothill areas.

The overload factor, which was renamed "load safety factor" and the new designation γ_f remained at 1.4 for most cases. When calculating the structural roof elements, for which the ratio of the considered normative value of the uniformly distributed load from the weight of the roof to the normative value of the snow cover S_0 weight is less than 0.8, it was prescribed to take γ_f equal to 1.6. For cases that should provide for the consideration of rheological processes in structures, special reduced standard values of the snow load were established without a statistical justification, obtained by multiplying the full design values by coefficients 0.3 for the III snow region; 0.5 – for the IV region; 0.6 – for V and VI regions.

A number of researchers have identified significant shortcomings of SNiP 2.01.07-85 in terms of the snow load regulation [18-20]. With the collapse of the USSR, the new states had the opportunity to move away from the coarse Soviet snow rationing and develop their own, more differentiated snow zoning. Further development of snow codes on the territory of the CIS was realized in the form of national codes of each state.

Russia followed the path of gradual development of SNiP codes. The Code of Rules SP 20.13330.2011 “Loads and effects”, an updated version of SNiP 2.01.07-85*, was developed. It introduced a new principle for standardizing the weight values of the earth's snow cover, in accordance with the highest annual values exceeded, on average, once every 25 years. They are determined according to the data of ten-day route snow surveys on the largest reserves of water in the snow cover in areas protected from direct wind impact (in the forest under tree crowns or forest glades) for at least 20 years. In this case, the data of Roshydromet were used for more than 4600 meteorological stations and posts with a row length of 20 ... 45 years, obtained by directly measuring the weight of the snow cover using a weight snow meter. On the basis of the outlined basic provisions, a new zoning map of the Russian territory was developed according to the estimated weight of snow cover, on which the boundaries of 8 snow regions (instead of 7 in the previous codes) were plotted with regional values in the range of 0.80 ... 5.60 kPa [20, 21]. Region values have increased markedly in comparison with the corresponding design values according to the previous standards. For example, for the III region, the design value became equal to $S_g = 1.8$ kPa in comparison with the previous calculated value $S = S_0 \gamma f = 1.0 \cdot 1.4 = 1.4$ kPa. In this edition of the snow codes, the same principle is applied that was used earlier in the rationing of snow loads when territories with a snow cover weight about 2/3 more and 1/3 less than the accepted regional values were included in one region. SP 20.13330 “Loads and effects” defines the normative value of the snow load on the horizontal projection of the roof as a base value:

$$S_0 = 0.7\, c_e\, c_t\, \mu\, S_g\,, \tag{2}$$

where S_g is the weight of the snow cover per 1 m^2 of the earth horizontal surface, the procedure for determining which is described above;

c_e – coefficient of the possible drift of snow from the building roof under the influence of wind or other factors (previously indicated as k and k_1);

c_t – coefficient of reduction of snow load due to the effect of temperature (previously did not have a special designation);

μ – coefficient of transition from the weight of the earth snow cover to the snow load on the roof.

To switch to the calculated value of the snow load, the load safety factor $\gamma_f = 1.4$ is used.

As in SNiP 2.01.07-85, the scope of the explicitly introduced snowdrift coefficient extends to gentle (with slopes up to 12% and with $f/l \le 0.05$ roofs of single-span and multi-span buildings without lanterns designed in areas with average wind speed for the three coldest months $V \ge 2$ m/s. The formula for determining this coefficient has been slightly changed

$$c_e = (1.2 - 0.1V\sqrt{k})(0.8 - 0.002b)\,, \tag{3}$$

where k is a coefficient that takes into account the change in wind pressure along with the height;

b – the roof width, taken no more than 100 m.

In addition, the coefficient c_e is introduced for spherical and conical roofs of buildings on a circular plan. The specified Code of Rules for the first time determines the possibility of using the thermal coefficient to take into account the reduction of snow loads on roofs with a high heat transfer coefficient (*>1 W/(m^2°C)*, leaving its justification for the developers of special recommendations. At the same time, similar to the previous editions of SNiP, the coefficient c_t is taken equal to 0.8 for non-insulated roofs of workshops with increased heat release, provided that meltwater is removed from the roof with a slope of more than 3%.

Unlike the previous version of the codes, the reduced normative value of the snow load is determined regardless of the snow region by multiplying the full normative value by a factor of 0,7, except for areas with an average January temperature above minus 5C.

Despite a significant increase in the design values of snow loads in the considered version of the Russian codes, there were some critical remarks about the method of snow rationing in Russia. In particular, Maliy V.I. (TsNII Proektstalkonstruktsiya) [24] harshly criticized the main criterion of this rationing – the use of a 25-year repetition period of the annual maximum to substantiate the design values of the snow load. In support of this, data was given that in the Moscow region over 100 years of observations, the snow load reached 2.1 kPa at a rate of 1.8 kPa according to SP 20.13330.2011 “Loads and effects”. The critic also drew on a well-known independent test scheme to show the high probability of exceeding the design value of 1.8 kPa over a period of 100 years. Taking this into account, as well as the example of the Eurocode standards, which use an additional safety factor of 1.5, a proposal was made to increase the design snow load to 3.0 kPa for the Moscow region. The developers of the codes from TsNNIISK strongly disagree with this [22, 23]. In principle, one can agree with them, since the load standards should be considered not in isolation for individual loads, but as part of a general assessment of the structures reliability [25]. Maliy V.I. also criticizes the principle of zoning the weight of the snow cover, when points which differ from the regional ones, both to a greater and a lesser extent, are combined into regions for the purpose of unification. A number of publications note that the zoning of the Russian territory according to the design snow loads still does not fully take into account the variability of the snow load in the area, and alternative approaches to snow rationing are proposed [26].

Ukrainian specialists, in contrast to the Russian developers of the codes, prepared the State Norms of Ukraine DBN V.1.2-2006 "Loads and effects", conceptually different from SNiP in terms of snow loads. The probabilistic representation of loads, including snow loads on building structures, was significantly developed. Such mathematical models have been developed as stochastic processes, absolute maxima of stochastic processes, independent test schemes, discrete representation, extremes, and correlated random sequence of overloads [27]. This made it possible for the first time to substantiate a probabilistic model for the snow load in the form of a quasi-stationary differentiable random process with a stationary frequency structure and an annual seasonal trend of the mathematical expectation and standard [28]. For the snow load of Ukraine, which has an unstable nature, a relatively little-known bimodal distribution, called "polynomial-exponential", was successfully applied:

$$f(\gamma) = \exp\left(C_0 + C_1\gamma + C_2\gamma^2 + C_3\gamma^3\right), \tag{4}$$

where $\gamma = (x - \bar{x}) / \hat{x}$ is the normalized deviation of the load from its mathematical expectation $\bar{x}$;

$\hat{x}$ – standard (standard deviation).

The statistical characteristics of this probabilistic model were calculated based on data from over one hundred meteorological stations located in the territory of Ukraine. They are summarized in publications [19, 29]. Due to sufficient information provision, the probabilistic model of a quasi-stationary random process has been successfully applied to normalize the snow load in the DBN. For this, the results of snow surveys were used, carried out at 222 meteorological stations and posts in Ukraine during 1950 ... 1990 with the duration of climatic series from 21 to 35 years. In general, a representative sample of more than 100 thousand snow survey results was used to normalize the snow load in Ukraine.

The DBN consider the snow load as a variable load with three design values: limiting S_m, operational S_e, and quasi-constant S_p (5):

$$\begin{gathered} S_m = \gamma_{fm}\, S_0\, C\,; \\ S_e = \gamma_{fe}\, S_0\, C\,; \\ S_p = (0.4 S_0 - 160)\, C\,, \end{gathered} \tag{5}$$

where S_0 – the characteristic value of the snow load, equal to the weight of the snow cover per 1 m^2 of the earth surface, which can be exceeded on average once every 50 years (similar to the Eurocode), is taken from the map of territorial zoning of Ukraine;

γ_{fm} and γ_{fe} – respectively, the safety factor for the limiting and operational design value.

The reliability factor for the limiting design value γ_{fm} is presented in tabular form in the range 0.24 – 1.44 depending on the specified repetition period of the snow load $T = 1 - 500$ years. The reliability factor for the operational design value γ_{fe} is presented in tabular form in the range 0.88 – 0.10, depending on the fraction $\eta = 0.002 - 0.1$ of the established service life of the structure, during which this value may be exceeded. Giving reason to the quasi-constant design value of the snow load, the phenomenon of concrete creep under load was taken as the basis, as the most common rheological effect, which is taken into account in the calculations of building structures [30]. The values of the coefficients and the design values of the snow load in the formula (5) have a statistical justification [19].

The features of a particular roof are taken into account by a coefficient C determined by the expression:

$$C = \mu\, C_e\, C_{alt}\,, \tag{6}$$

where μ is the coefficient taking into account the roof profile, adopted mainly according to the recommendations of SNiP, but expanded with the involvement of the Eurocode data;

C_e – coefficient taking into account, similarly to SNiP, the operating mode of the roof;

C_{alt} – coefficient of geographic height H, taken as $1.4H + 0.3$ for $H\ \varepsilon\ 0.5$ km.

The generalized statistical data testified to significant territorial variability of the snow load, which significantly differed from its standardization of SNiP, according to which almost the entire territory of Ukraine belonged to the least snowy regions I ($S_0 = 0.5$ kPa) and II ($S_0 = 0.7$ kPa). Meanwhile, the experimentally substantiated design values of the snow load corresponding to the base average repetition period $T = 50$ years vary from 0.76 kPa for the Kherson region to 1.79 kPa in the northeastern regions of Ukraine. Attention is drawn to the rather high values (1.20...1.80 kPa) of the snow load recorded at some southern meteorological stations. The analysis of experimental data, in addition, confirmed that in Ukraine there are especially snowy winters, for example, in 1963–64, 1966–67 and 1986–87. In some points, the largest weight of the snow cover exceeded 2.0 kPa, which, nevertheless, did not fall out of the total set of annual maximums.

The territorial zoning of Ukraine according to the characteristic values of the weight of the snow cover was carried out according to the method developed by V.A. Pashinsky [19]. A probabilistic model of a non-stationary normal random field was used, the ordinates of which were the values of the loads for individual meteorological stations located at distances of 30 ... 60 km. The smoothing procedure made it possible to obtain a smooth surface of the mathematical expectation of the snow load, free from random fluctuations in the data of individual meteorological stations. The regional values of the design snow load were set so that the excess reserves of territorial zoning were minimal. As a result, six territorial regions with characteristic values from 0,8 to 1,8 kPa were allocated on the territory of Ukraine. At the same time, it was revealed that the actual design loads exceed the regional ones by no more than 12%, for 21% of meteorological stations. At the same time, due to the necessary generalization, the values increased by an average of 16,4% and in some cases exceeded the actual loads by 50%.

It should be emphasized that the limiting design values of the snow load included in the DBN in most cases exceed the corresponding values established by the SNiP. On the one hand, this leads to an increase in the cross-sections and material consumption of the supporting structures of the roofs, but on the other hand, to an increase in their level of reliability. At the same time, a noticeable increase in the calculated values of the snow load leads to a smaller increase in material consumption. So, for example, at $T = 50$ years, the design values of the snow load increase on average by 58%, and the mass of steel trusses for a light roof – by only 22% [19].

Giving a general assessment of the Ukrainian codes DBN V.1.2-2006 "Loads and effects" in terms of snow load, it should be emphasized that they are compiled on a modern methodological basis, are close to the Eurocode, are based on representative statistical material, are more differentiated and have a scientific probabilistic basis more deeply developed than the codes of previous years.

In subsequent years, probabilistic studies of snow load continued in Ukraine, the practical results of which were recommendations for improving design codes. Kinash R.I. proposed an alternative method for zoning snow loads for the territory of Ukraine [18]. Proposals were developed for a more detailed snow zoning of the mountainous Carpathian region (within the boundaries of the Transcarpathian region) with the introduction of additional 5 regions (from 7th to 11th) with characteristic snow loads in the range of 2.2 ... 3.0 kPa [31]. The probabilistic research of snow loads was continued by the scientific school of building structures reliability of the Yuriy Kondratyuk Poltava National Technical University [35]. Snow accumulation on the roofs with height discontinuity was studied, which gave a practical result in the form of a statistically substantiated combination coefficient of 0.8 for snow bags on the territory of Ukraine [32]. A probabilistic assessment of the influence of the building roofs thermal characteristics on the snow load value is carried out. The results of this work are presented in the form of a differentiated coefficient of roof operation [33]. Design snow loads on cold roofs of buildings with positive indoor temperatures were determined [34].

Conclusions

It is shown that over the past eighty years, domestic codes for the design of building structures in terms of the regulation of snow loads have undergone significant changes and have expanded their statistical foundations. Territorial snow zoning has developed, the number of snow regions has increased, especially on the territory of Ukraine. The substantiation of the normative (characteristic) and design values of the snow load was modified on the basis of an increased return period. A probabilistic account of wind drift of snow from roofs has been developed and included in the codes, and a quasi-constant value of the snow load has been statistically substantiated. The high scientific level of domestic standards DBN V.1.2-2006 "Loads and effects", that have a modern statistical basis, which is associated with the Eurocode and provides the required level of reliability of building structures, is noted. New scientific results are highlighted that can be included in subsequent editions of snow load codes.

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